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SEDIMENT YIELD VARIABILITY IN THE UPPER YANGTZE, CHINA

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ABSTRACT

The development and increasing availability of global environmental data sets provides an opportunity to examine systematically the relationship between sediment yields and controlling catchment variables, employing Geographical Information Systems. Few studies have attempted to harness such information to analyse variations in sediment yields *within* large catchments. Sediment yields from 62 long-term gauging stations within the catchment of the Upper Yangtze River, China, have been analysed in relation to variables describing hydrology, climate, topography and population density. This analysis is particularly significant as the 10^6 km^2 catchment area of the Upper Yangtze will shortly be impacted by the world's largest dam scheme (the Three Gorges Project). There is a high degree of scatter in sediment yields because of natural diversity in the catchment, but this scatter is reduced when the data are grouped according to tributary location, catchment size and maximum elevation. Sediment yields generally increase with precipitation, runoff and population density and decrease with elevation, but there is evidence of scale dependency and of variation between geographic regions within the basin. The small number of variables used are capable of explaining the majority of variance in the comparatively 'natural' western tributaries but are less adequate in areas affected by large-scale agricultural activity. In future, improvements in the resolution and accessibility of environmental data sets will allow more detailed analysis of regional variability in sediment yield. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: sediment yield; global environmental data sets; Upper Yangtze River; Three Gorges

INTRODUCTION

The Upper Yangtze, upstream of Yichang, Hubei Province, China, includes a diverse range of environments. The Yangtze rises on the arid Qinghai-Tibet (Xizang) Plateau, where a large proportion of the land is at an elevation above 4000 m, before descending into the fertile Sichuan Basin. The Upper Jinsha, Yalong, Dadu and Min drain the mountainous west, the Tuo, Fu, Jialing and Qu drain the agricultural lands of Sichuan in the east of the catchment, and the Wu drains the uplands of Guiyang province (Figure 1). The proposal to construct the world's largest hydro-power scheme on the Yangtze (the Three Gorges Project, TGP) has focused attention on the implications of soil erosion and fluvial sediment transport in the Upper Yangtze basin. The life span of the scheme could be threatened by extensive sedimentation although the dam engineers are confident that river regulation procedures can reduce this hazard (Qian *et al.*, 1993). Widespread evidence that the extent and magnitude of soil erosion has increased dramatically during the last 40 years (Edmonds, 1992; Wen, 1993) is not clearly matched by trends in the sediment load measured at Yichang, a long-term gauging station a short distance downstream of the TGP dam site (Figure 1). Two key questions for those involved in catchment management concern identification of the main sources of sediment and their conveyance to the main Yangtze channel. A number of studies have examined temporal and spatial patterns of sediment transfer in the Upper Yangtze (Gu *et al.*, 1987; Gu and Douglas, 1989; Qian *et al.*, 1993; Zhou and Xiang, 1994; Higgitt and Lu, 1996), but there has been little attempt systematically to examine the relationship between sediment yield and its controlling variables.

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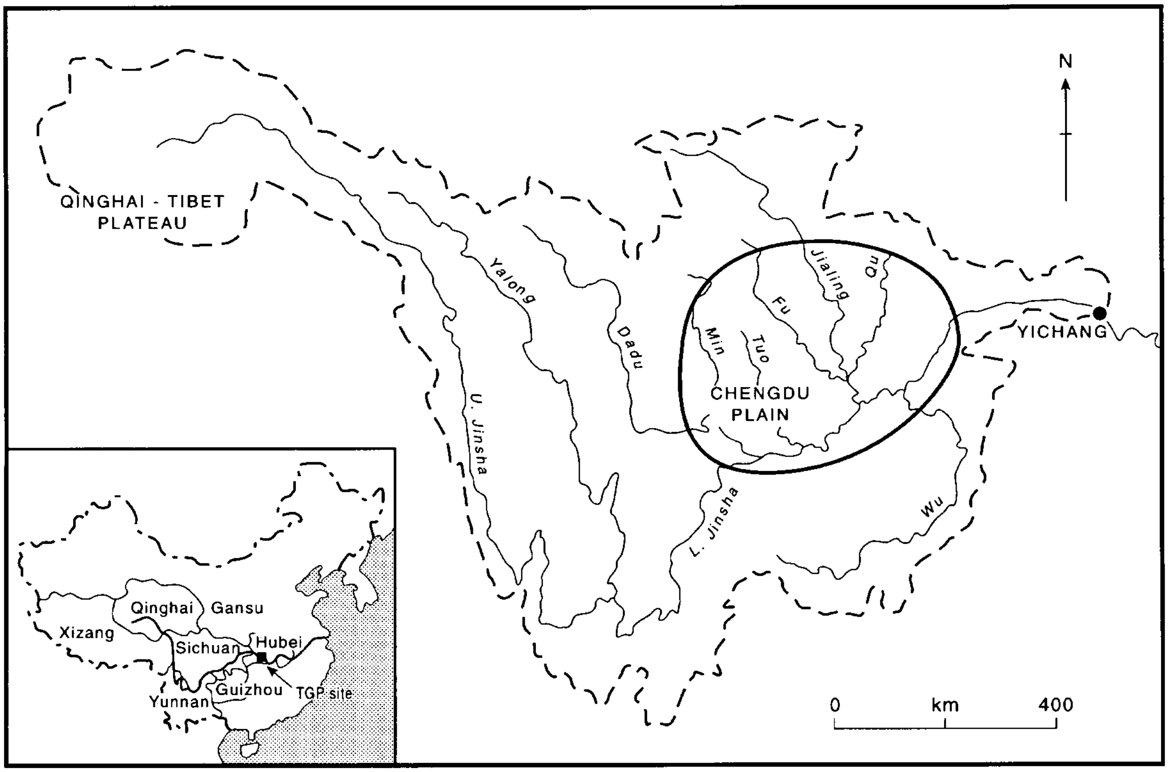

Figure 1. The Upper Yangtze Basin. Major areas of level ground on the Qinghai–Tibet Plateau and the Chengdu Plain (part of the Sichuan basin) are indicated. The inset shows the regional setting and the names of provinces in the area

Several attempts have been made to explain global and regional patterns of sediment yield in terms of either climate and vegetation (Langbein and Schumm, 1958; Douglas, 1967; Wilson, 1973; Jansen and Painter, 1974; Jansson, 1988) or topography (Milliman and Syvitski, 1992; Summerfield and Hulton, 1994). Within China, Xu (1994) has proposed that national variations in sedimentation are adequately described by the Langbein–Schumm model, but inspection of sediment load data within the Upper Yangtze suggests greater complexity, reflecting the combination of topographic, hydroclimatic, lithological, land-use and soil erodibility controls. Attempts to assess the relative importance of these controls in explaining patterns in sediment yield have been hampered by the difficulty of obtaining sufficiently detailed, spatially distributed information. However, the advent of global environmental data sets containing description of the hydroclimatic, biological and geomorphological characteristics of the Earth (Ludwig and Probst, 1996) offer the potential for extracting catchment variables for integration with sediment yield data. The resolution of global data sets has tended to restrict previous analyses to the global scale, where individual catchments are represented by single sediment yield variables (Summerfield and Hulton, 1994; Ludwig and Probst, 1996). The application of such an approach to a large basin ($>10^6$ km^2) containing a hierarchy of nested gauging stations appears to have received limited attention.

To address this limitation, the principal aim of the paper is to examine the controls on sediment yield within the Upper Yangtze basin, using catchment data extracted from various global data sets. Recognizing that many relationships are widely scattered, attempts are made to reduce scatter through screening analyses based on geographic location (tributary), catchment size and elevation. Previous work has described spatial and temporal variations in sediment load (Higgitt and Lu, 1996; Lu and Higgitt, 1998a) and approaches to mapping regional sediment yields (Lu and Higgitt, 1998b).

DATA SOURCES AND METHODS

Sediment yield and runoff data

Sediment yield (SY) and runoff (RO) data are derived from a network of hydrographic stations throughout the Upper Yangtze. Some river gauging records extend back to the 1930s, but the majority commence in the 1950s. The original records for each station provide information on station co-ordinates (latitude and longitude), catchment area, mean monthly and annual water discharge and sediment load, and the magnitude and date of occurrence of the maximum daily discharge. Load data refer to measured suspended sediment and exclude any bedload. The annual measured sediment loads were recorded in units of 10^6 or 10^4 t depending on the station basin area or measurement year and it is apparent that the compilation of records into yearbooks has introduced some errors in these units (Higgitt and Lu, 1996). Recalculation of annual load from monthly load data has enabled several of these transcription errors to be corrected. The recorded catchment areas and locations of many stations are inconsistent within the measurement series and might reflect correction of previous area measurement or a slight change of station location. Error is also introduced through the use of daily or weekly measurements, rather than continuous monitoring, which is likely to underestimate sediment discharges during peak flows (Waythomas and Williams, 1988).

Sediment load data were extracted from 250 stations in the Upper Yangtze for the period 1956–1987. As the catchment experiences marked year-on-year climatic variations, it was decided to restrict analysis of the relationship between sediment yield and potential controlling variables to those stations with 25 or more years of record (Table I). Data for 56 stations which met this criterion were supplemented by a further six stations from the Wu tributary. The resulting distribution of the stations comprises 17 in the Jinsha–Yalong catchment, 15 in the Dadu–Min (including Tuo), 20 in the Jialing, six in the Wu and four in the catchment area of the Main channel. Summary information describing these stations is listed in Table II.

Sediment outputs from catchments of different sizes are normally expressed as specific sediment yields (t km^{-2} a^{-1}). There are two approaches to calculating specific sediment yields in hierarchical sub-catchments. First, they can be calculated by deducting the sediment load at the immediate upstream station from that at the gauging station, and then dividing this value by the incremental catchment area (Lajczak and Jansson, 1993; Ozturk, 1996). This method is problematic at stations where there is a net loss of sediment load downstream (for example, through floodplain deposition), as this will produce a negative value, especially in downstream reaches of large rivers. The alternative approach, which is used here, is to express specific sediment yield as total load divided by total catchment area upstream of the station, although this means that the problem of spatial averaging is accentuated in the downstream direction. The influence of scale on relationships between sediment yield and catchment variables requires further consideration.

Table I. Gauging station length of record and catchment areas

Measurement years	Numbers	Percentage	Catchment area (km^2)	Numbers
1–4	63	25·2	<100	1
5–9	30	12·0	100–1000	60
10–14	22	8·8	1000–10 000	119
15–19	29	11·6	10 000–100 000	48
20–24	50	20·0	100 000–1 000 000	21
25–32	56	22·4	>1 000 000	1
Total	250	100	Total	250

Table II. Mean specific sediment yields of the selected sub-catchments

No.	Tributaries	Stations	DA (km^2)	Years	Mean (t km^{-2} a^{-1})	SD	Min.	Max.
1	Jinsha-Yalong	Zimenda	137 704	28	68	38	9	139
6		Shigu	232 651	28	91	42	30	182
16		Huatan(Qiaojia)	450 696	30	366	133	221	707
23		Ninnan	3074	25	1191	764	330	3193
25		Qianxinqiao	2549	27	65	40	22	177
29		Meigu	1607	25	1152	653	473	3103
30		Pingshang	485 099	31	505	177	260	1034
31		Hengjiang	14 781	25	919	367	429	1629
32		Zhutuo	694 725	26	459	102	296	668
36		Dianwei	120	29	262	245	20	931
42		Qinkoutang	2109	29	798	364	272	1629
64		Lounin	108 083	28	175	79	77	333
67		Xiaodeshi	118 294	27	249	114	107	544
69		Anninqiao	937	27	657	372	238	2159
70		Sunshuiguan	1596	26	1770	1523	350	7237
71		Manshuiwan	3817	32	975	659	263	3042
73		Wantan	11 100	26	973	587	389	2707
81	Dadu-Min	Zengjianguan	4486	27	124	72	38	295
83		Shaba	7231	31	344	211	94	1034
84		Jiangsheba	14 279	26	307	198	75	915
85		Zagunao	2404	26	284	170	63	810
86		Shuangping	4629	30	387	216	145	1145
91		Yanliuping	363	26	812	794	23	3695
92		Xinxinchang	396	26	1257	1242	139	5315
94		Pengshan	30 661	30	337	157	131	721
97		Qinshuixi	3330	28	487	230	86	1346
98		Gaochang	135 378	32	363	160	167	897
105		Dajin	40 484	27	107	53	31	266
116		Shaping	75 016	21	420	146	189	732
125	Tuo	Shanhuangmiao	6590	28	853	440	204	1954
128		Denyenyan	14 484	31	617	365	73	1571
129		Lijiawan	23 283	29	537	351	94	1532
133	Jialing	Yunninzeng	2071	25	458	420	46	1513
140		Liuanyang	19 206	30	1706	1327	273	6638
149		Wudu	14 288	25	1194	860	223	4660
153		Bikou	26 086	27	632	453	79	1609
154		Sanleiba	29 247	29	563	359	110	1381
156		Tinzhikou	61 089	28	1027	644	196	2681
160		Qinquanxian	5011	25	598	562	96	2821
164		Wusheng	79 714	31	928	562	123	2542
165		Beipei	156 142	31	955	469	189	2284
168		Bixi	2124	28	661	475	55	1605
171		Qilitou	6382	27	586	393	72	1389
178		Dunlin	6462	29	1216	726	273	3394
179		Minyuantan	736	27	1108	447	423	2024
180		Guodukou	31 626	30	630	344	102	1517
182		Jinbian	2740	27	395	263	31	1022
183		Luoduxi	38 071	31	760	442	94	1757
189		Fujiangqiao	11 903	25	992	921	139	4056
190		Guanyinchang	1933	26	228	172	14	726
195		Shehong	23 574	29	705	527	43	2584
197		Xiaoheba	29 420	30	650	566	59	3121
200	Wu	Yachihe	16 541	21	886	409	193	1727
201		Wujiangdu	26 496	23	498	305	9	1131
206		Shinan	50 791	21	345	186	17	746
207		Wulong	83 035	27	390	148	134	730
208		Gongtan	58 346	21	366	149	70	719
220		Duntou	6917	26	94	49	17	176
236	Main channel	Chuntang	866 559	30	518	127	333	823
242		Shizhu	898	25	719	1013	157	5377
243		Wanxian	974 881	20	503	122	346	819
250		Yichang	1005501	31	524	98	361	725

Catchment boundary delineation

Identification of boundaries to each sub-catchment is an essential stage in extracting spatially distributed variables using a geographical information system (GIS). Given the co-ordinates of the gauging station, a high resolution digital elevation model (DEM) can be employed to derive catchment boundaries and, hence, most catchment morphometric variables. The Asian 30 arcsecond DEM has the highest resolution elevation data available in the public domain for this part of China. The primary source of the DEM was a generalization of the Level 1 Digital Terrain Elevation Data (DTED) produced by the US Defense Mapping Agency. Elevation data for the areas of Asia which are not covered by the DTED were developed for the Asian 30 arcsecond DEM, using the 1:1 000 000 scale Digital Chart of the World. The original 3 arcsecond DTED data for Asia have been resampled to produce the Asia 30 arcsecond DEM, which yields an accuracy of approximately ± 1 km across the latitude range of interest. Vertical resolution is ± 30 m.

Using the available DEM, some catchment boundaries were delineated using Arc/Info GIS (ESRI, 1994). However, it is difficult to generate catchment boundaries in relatively flat areas such as the lower Jialing tributary in the Chengdu Plain part of Sichuan Basin. Some catchments were therefore digitized from 1:1 500 000 maps. There is good agreement between the delineated/digitized catchment areas and the recorded catchment areas, although the resolution of the DEM and topographic map is low. Discrepancies between the delineated/digitized and the recorded areas were generally small. For example, differences of <5 per cent were identified for 40 (64·5 per cent) of the 62 catchments and differences of 5–10 per cent were found for 19 (30·6 per cent) of the catchments. Only three catchments had differences as large as 10 to 15 per cent (4·7 per cent).

Extraction of catchment variables

The following variables were extracted for each of the 62 sub-catchments defined by the catchment boundaries: mean elevation (ME; m), basin relief (BR; m), mean slope (MS; degrees), population density (PD; persons km^{-2}) and precipitation (PP; mm).

Mean elevation is defined by the arithmetic mean of the elevations of all cells within the catchment boundary, while basin relief is the difference between maximum and minimum cell values. Mean, maximum and minimum cell values for each catchment were obtained from a statistical file after clipping the 30 arcsecond DEM using the delineated/digitized catchment boundary. A slope grid was generated using slope commands in Arc/Info, from which mean slope, defined by the mean of the slopes of all cells, was extracted for each catchment. The slope was calculated based on maximum elevation changes within nine neighbouring cells (ESRI, 1994). Clearly, at the resolution involved, slope is a rather crude indicator of topographic variation.

Population density data were derived from the Asian Population Database (APD). The development of the APD was supported by the United Nations Environment Programme/Global Resource Information Database (UNEP/GRID) and the Consultative Group for International Agricultural Research (CGIAR). The Asian population database is part of ongoing effort to improve global, spatially referenced demographic data holdings. Such databases are useful for a variety of applications including strategic level agricultural research and applications in the analysis of the human dimensions of global change. This project has pooled available data sets, many of which had been assembled for the global demography project. For China, the data were products of the 1992 census. Data from APD were downloaded from the Internet and converted into gridded data using Arc/Info.

Precipitation data were derived from the Global Ecosystems Database (GED) version 1 (NOAA-EPA Global Ecosystems Project, 1992) which is an integrated database related to global environmental and ecological change. The database contains many useful map distributions, such as cultivation intensity and soils, with resolutions varying from 10×10 minutes to 1×1 degree. Unfortunately, the resolutions for most variables are poor across China, making them unsuitable for this scale of regional study. Consequently, only annual and monthly average precipitation data, at a resolution of $0{\cdot}5 \times 0{\cdot}5$ degree (Legates and Willmost, 1992) were considered suitable for the current analysis. Average annual precipitation was defined as the mean for all cells within the catchment boundaries.

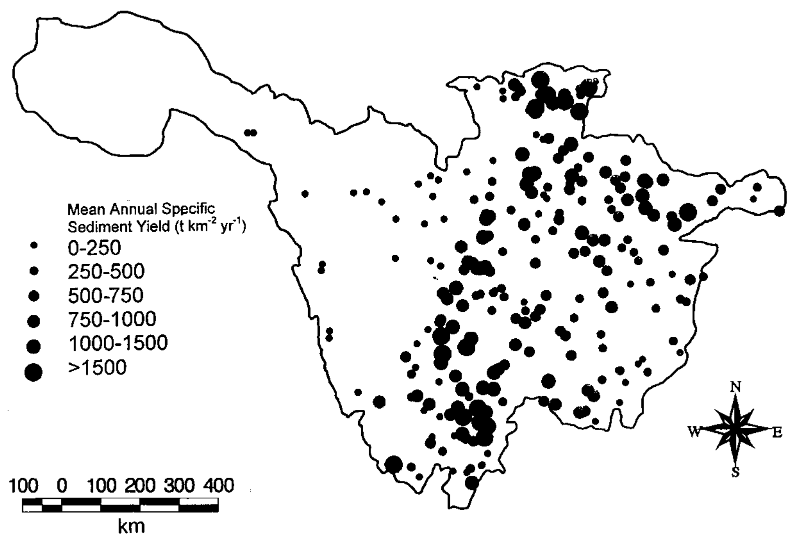

Figure 2. Distribution and range of mean specific sediment yield (t km^{-2} a^{-1}) in the Upper Yangtze Basin

RESULTS

This section is divided into three parts. First, the spatial distribution of the extracted data is examined and general geographical patterns are described. Second, the interrelationships between the catchment variables are examined as it is likely that there will be some collinearity between variables. Third, variation of sediment yield with catchment variables is examined through grouping data by tributary, catchment size and maximum elevation to reduce scatter.

Sediment yield variability and catchment variables

Mean annual specific sediment yields (t km^{-2} a^{-1}) for all Upper Yangtze stations with five or more years of record are plotted in Figure 2. It is well known that specific sediment yield declines with catchment area as opportunities for sediment storage increase (Walling, 1983). In an earlier paper, Higgitt and Lu (1996) represented sediment yields as standardized residuals from the specific sediment yield–catchment area regression. Nevertheless, the raw data illustrate the spatial pattern of sediment yields and indicate that the gauging stations are distributed unevenly, with most located in the populated east and few in the mountainous west. The upper Jialing and the lower Jinsha have much higher sediment yields than the upper Jinsha and Yalong tributaries. Using standardization procedures, Higgitt and Lu (1996) found that the catchments of the Jialing, Fu and Qu rivers were the dominant sediment source area, but showed that the relative importance of Jialing declined during the 1970s, whereas the Qu became an increasingly important source throughout the period.

Information on topography, slope, precipitation and population densities are displayed in Figure 3. The topographical map (Figure 3 a) is produced from the Asian 30 arcsecond DEM based on five classes, 0–200, 200–500, 500–1000, 1000–3000 and >3000 m. It emphasizes the large area of high elevation on the Qinghai–Tibet plateau and the very deep and narrow valleys draining it. A large number of the sub-catchments in the sediment yield data set contain land above 3000 m, in contrast to previous studies of global or regional controls on sediment yield which are skewed towards lower elevations (Milliman and Syvitski, 1992; Probst and Amiotte-Suchet, 1992; Summerfield and Hulton, 1994).

The slope map indicates that the steep areas (>10°) are mainly distributed on the western margins of the Sichuan Basin and along the incised valleys of the Jinsha, Yalong and Dadu tributaries. There are two relatively flat areas, the Chengdu Plain and Qinghai–Tibet plateau (Figure 1), where the dominant mean slope angle is less than 1°. However, it should be noted that many flat areas (recorded as 0°) are generated by the

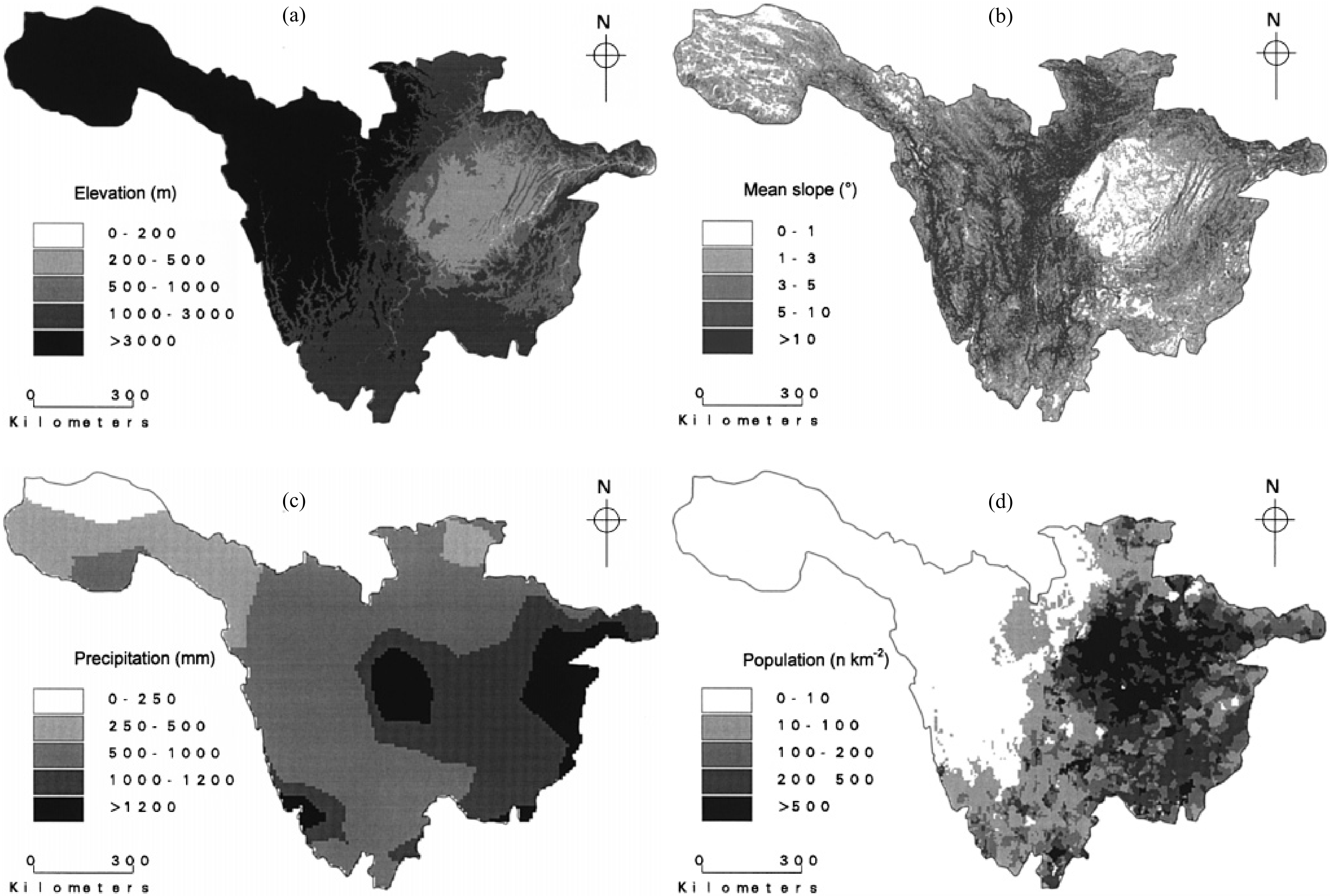

Figure 3. Distribution maps of mean cell values for (a) elevation (m), (b) slope (degrees), (c) mean annual precipitation (mm) and (d) population density (persons km^{-2})

GIS due to problems inherent to the resolution of the DEM. This problem must be taken into account when the slope is applied in sediment yield modelling.

The precipitation map also emphasizes the dramatic contrast between the arid/semi-arid northern Qinghai–Tibet Plateau and the eastern part of the basin, where precipitation exceeds 1000 mm. The Qinghai–Tibet plateau has a significant influence on atmospheric circulation not only regionally but perhaps over the entire northern hemisphere (Ruddiman *et al.*, 1989). The plateau constrains penetration of the monsoon, resulting in a complex pattern of precipitation within the Upper Yangtze catchment.

Population densities are generally inversely related to elevation, with values ranging from less than 10 people km^{-2} in the Qinghai–Tibet Plateau to >500 persons km^{-2} in the Sichuan Basin, which has one of the highest population densities in China. The total population of Sichuan province exceeds 0·1 billion. The Jialing, Tuo and Wu flow through the higher population density areas.

Interrelationships between catchment variables

The GIS environment enables values for both individual cells (pixels) and sub-catchments to be calculated efficiently. Examination of the interrelationships between these catchment variables precedes analysis of their relationship to sediment yield. As many of the distributions of catchment variables do not closely approximate to normal distributions, and because the interaction between variables may not be linear, parametric statistical techniques are inapplicable. Results from a non-parametric Spearman's rank correlation matrix are presented in Table III. As expected, mean elevation is significantly correlated with many other variables. Mean slopes increase with mean elevation, whereas mean population density and precipitation decrease with mean elevation. However, the relationships are more complex at pixel level (Figure 4). The headwaters of the Jinsha and Yalong Rivers on the Qinghai–Tibet plateau are areas of gentle relief where the mean slope generally increases with elevation up to 2500 m but then decreases. Population density decreases sharply with elevation above 1000 m elevation. Elevation and precipitation are inversely related, but with a high degree of scatter in lower elevation areas.

Modelling sediment yield variability

The high degree of spatial variability in sediment yields and catchment characteristics causes difficulty when attempting to model controlling relationships using the whole data set. Considering the 62 selected catchments, specific sediment yields are significantly correlated with only mean elevation and runoff (Table III). The role of elevation as a direct control on sediment transport is questionable. Elevation, as a measure of potential energy, has an influence on erosion potential but in this case appears to act as a surrogate for aridity and human impact, both of which have negative correlations with elevation. The interdependence of variables likely to influence sediment production and transport is problematic. Simple relationships between sediment yield and a catchment variable, such as elevation, can reflect underlying influences. The use of multiple regression procedures to establish the optimum explanation of sediment yield from a selection of catchment variables must take into account the redundancy of each additional variable. In this case, stepwise procedures were used to examine the improvement in explanation provided by each additional variable. Attempts to explain controls on sediment yields are also subject to high degrees of scatter. Previous studies of sediment yields have attempted to reduce this scatter by grouping data into suitable categories. In global-scale studies, Milliman and Syvitski (1992) grouped sediment yield data by maximum elevation, while Ludwig and Probst (1996) and Jansson (1988) used climate type. The present study groups the 62 basins on the basis of tributary, basin size and maximum elevation.

Basin grouping based on tributary

Provision of an increased understanding of the controls on sediment production and output within each of the tributary basins will be important to the overall strategy for managing sedimentation in the Upper Yangtze. To this end, analysis is first based on tributary groupings: Jinsha–Yalong, Dadu–Min, Jialing (including Tuo) and Wu. As described above, a large proportion of the catchment areas within the Jinsha–

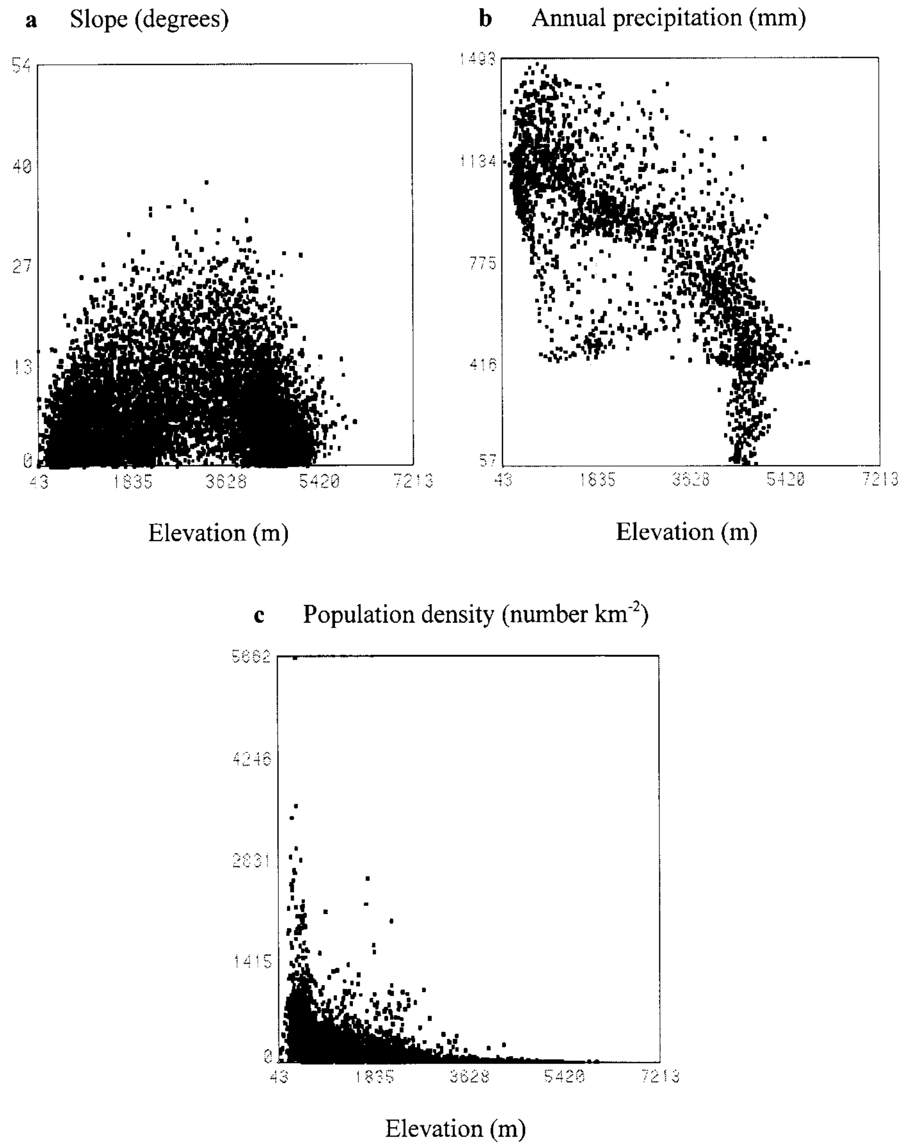

Figure 4. Scattergrams of (a) slope (degrees), (b) annual precipitation (mm) and (c) population density (persons km^{-2}) against elevation (m) at pixel level

Table III. Spearman's correlation matrix of catchment variables ($n = 62$)

	ME	BR	MS	PD	PP	RO	SY
ME	1						
BR	0·51**	1					
MS	0·63**	0·42**	1				
PD	−0·91**	−0·36**	−0·70**	1			
PP	−0·46**	−0·43**	−0·17	0·47**	1		
RO	−0·21	−0·14	−0·33**	0·14	0·67**	1	
SY	−0·31*	−0·05	0·21	0·23	0·11	0·39**	1

* Significant at 95 per cent level (critical value = 0·255)
** Significant at 99 per cent level (critical value = 0·335)

Yalong and Dadu–Min tributaries is located in areas with elevation >3000 m and low population density, while the Jialing and Wu, particularly their lower branches, are located in areas of lower elevation and high population density. However, the results of the analysis must be treated with caution because the group of stations for the Wu tributary contains only seven data points (the six stations listed in Table II plus Shizu (no. 242) which is a small Main Channel tributary close to the Wu–Yangtze confluence).

Specific sediment yield is plotted against all the variables in Figure 5. Generally, wide scatter remains in the data, despite the tributary groupings. Previous studies have used various strategies to reduce scatter. Milliman and Syvitski (1992) removed outliers defined by degrees of standard deviation and recalculated regression equations. Summerfield and Hulton (1994) argued that this procedure masked the real degree of scatter and proposed logarithmic transformation before calculation of Pearsonian correlation coefficients. In this study, instead of transforming the variables, curve-fitting techniques have been applied to the data in this study, with trendlines added to Figure 5 where relationships are significant at the $\alpha = 0{\cdot}05$ level. A number of the relationships between sediment yield and catchment variables are adequately described by second-or third-order polynomial equations, indicating the apparent presence of turning points or threshold conditions in the relationship.

There are marked contrasts in the range of significant correlations within each tributary grouping and in the nature of those relationships. The Jinsha–Yalong tributary has significant correlation with all variables except for basin relief. The decline of sediment yield with elevation may, at first, appear surprising but represents the transition from the high altitude, semi-arid Qinghai–Tibet Plateau to the deeply incised, sub-humid valleys downstream. Sediment yields increase consistently with runoff and precipitation. The Dadu–Min and the Wu groups have fewer significant correlations – precipitation and runoff in the former and only runoff in the latter. The Jialing has the same range of significant correlations as the Jinsha–Yalong, but there is some difference in the nature of the relationships. Sediment yields increase with elevation up to about 2000 m. Perhaps surprisingly, population density has an inverse relationship with sediment yield, although a greater impact through soil erosion might have been expected. Possible explanations are that the highest levels of population density within the catchment occur within the flat Chengdu Plain and that the more densely populated areas tend to have higher concentrations of water conservancy structures, which act to trap and store sediment. The polynomial relationships with precipitation and runoff are interesting. The apparent peak in sediment yield at an annual precipitation of 500 mm (or runoff around 250 mm) is similar to the classic model of Langbein and Schumm (1958), while the increase beyond 1000 mm precipitation (or 700 mm runoff) has some resonance with the global relationship described by Wilson (1973) and Walling and Webb (1983). However, this pattern is not repeated in the other tributaries. It should also be noted that some particularly high levels of sediment yield in the upper Jialing are associated with neotectonics and loess soil. For example, Liuanyang catchment (no. 140) recorded a 30-year average annual specific sediment yield of about 1700 t km^{-2} a^{-1} with a maximum exceeding 6600 t km^{-2} a^{-1} (Table II).

Basin grouping based on size

Analysis of the data grouped by tributary has some utility for recognizing the variation in controlling factors between different geographical locations and providing guidance for the implementation of conservancy operations, but relationships are obscured by scale effects reflected in relationships between specific sediment yield and basin size. As a compromise, the sub-catchments were grouped into four categories based on their size: <1000 (six catchments), 1000–10 000 (20 catchments), 10 000–100 000 (24 catchments) and $>100\,000$ km^2 (12 catchments). It was found that the relationships between sediment yield and catchment variables improved as catchment size increases (Figure 6). There are no significant correlations in the $<10\,000$ km^2 category. Better correlations are expected for larger catchments as variations due to land use, soil or geology are minimized. The $>100\,000$ km^2 group has strong, positive relationships with relief, population density and precipitation with a decline in sediment yields with elevation. Here again there are curious contrasts in the relationships with precipitation and runoff within the different groupings. A distinct minimum turning point at around 500 mm runoff is depicted by the polynomial trendline for the 10 000–100 000 km^2 catchments. There is also a general decline in sediment yield with precipitation within this

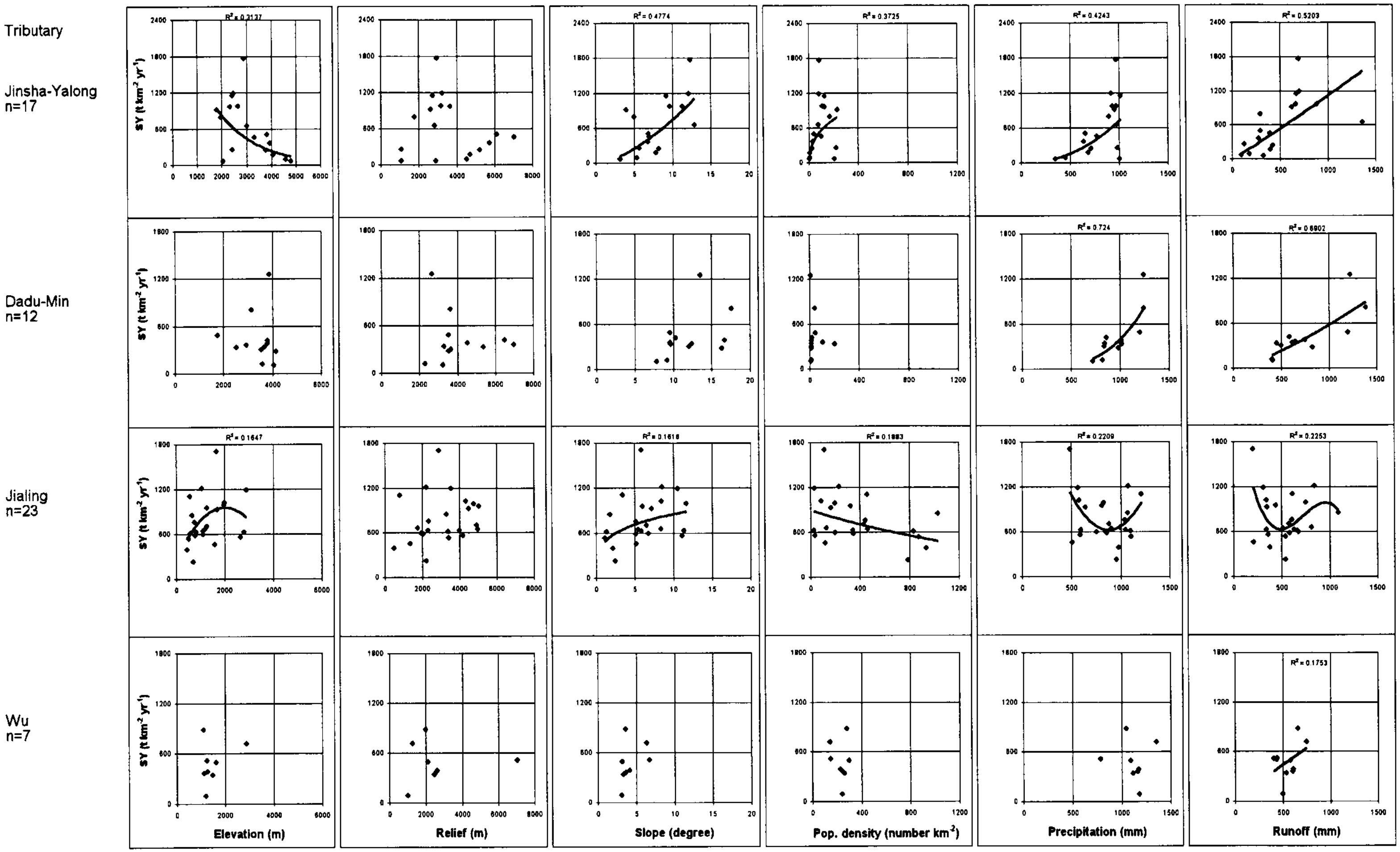

Figure 5. Relationships between specific sediment yield and catchment variables for the data grouped by tributary

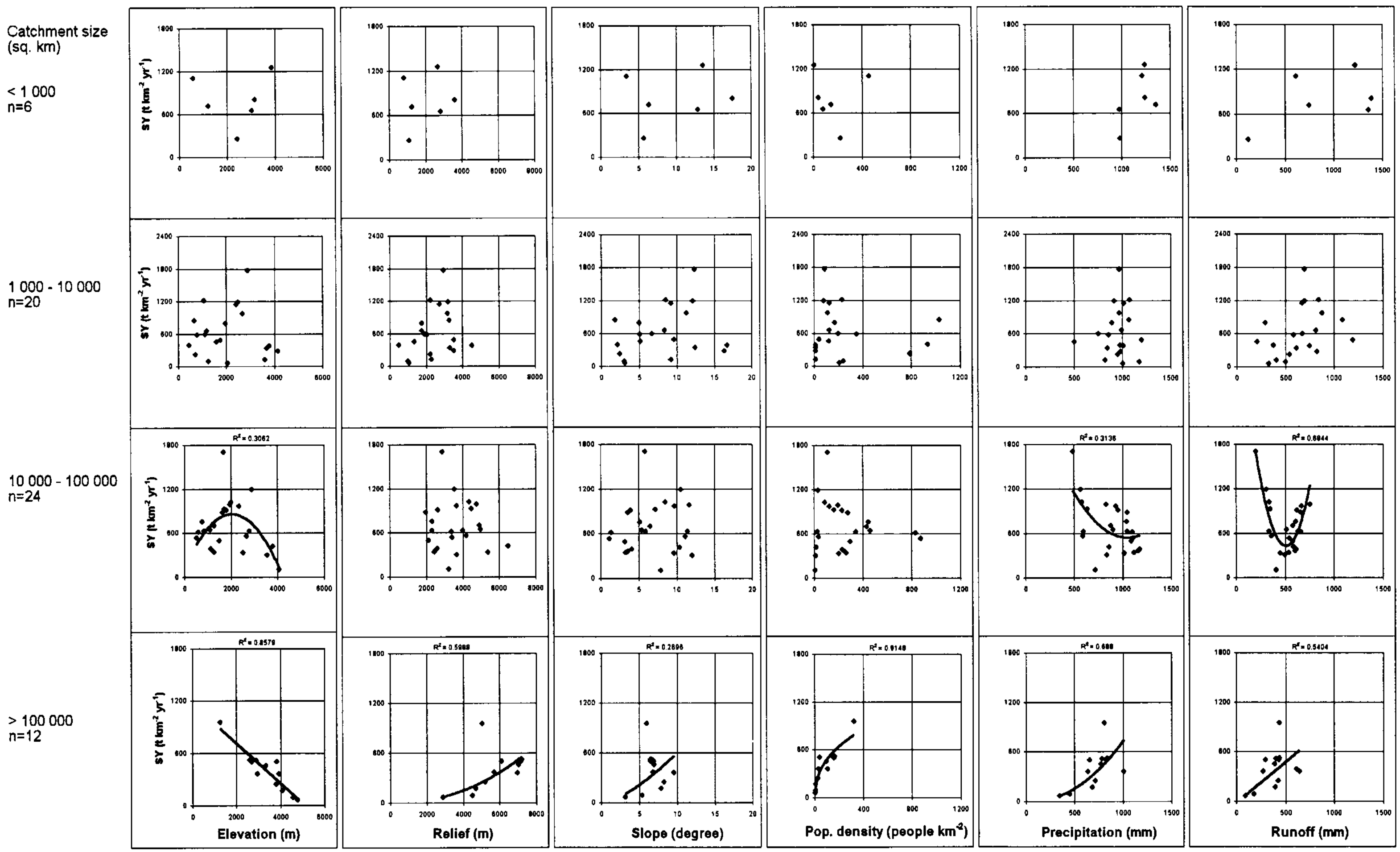

Figure 6. Relationships between specific sediment yield and catchment variables for the data grouped by catchment size

group in contrast to the relationship for larger catchments. Given the small sample sizes involved, the influence of outliers on the relationships may be significant.

Basin grouping based on maximum elevation

The importance of elevation as a control on other catchment characteristics was noted earlier. Milliman and Syvitski (1992) used maximum elevation groupings to demonstrate the relative importance of small mountainous basins in supplying a large proportion of terrestrial sediment to the oceans. The four classes used here are: <2500 (eight catchments), 2500–3500 (13 catchments), 3500–5000 (18 catchments) and >5000 m (23 catchments). The large number of catchments with maximum elevation greater than 5000 m contrasts starkly with those used in previous studies (Milliman and Syvitski, 1992; Probst and Amiotte-Suchet, 1992; Summerfield and Hulton, 1994), where the distribution is heavily skewed towards lower elevations. Relationships between sediment yield and catchment variables are highly scattered within lower elevation groupings (Figure 7). Sediment yields in lower elevation areas are likely to be influenced by agricultural activity that is not accounted for in the selected catchment variables. Stronger relationships are found in the >5000 m grouping, with the familiar inverse relationship evident between sediment yield and mean elevation. Positive relationships are found with population density, precipitation and runoff.

DISCUSSION: DISCRIMINATING CONTROLS ON REGIONAL SEDIMENT YIELD

Previous attempts to explain sediment yields in terms of a number of controlling factors have encountered high degrees of scatter. In this study, grouping of catchments by tributary, size and maximum elevation has provided a means of reducing scatter. Grouping has allowed the controlling factors on sediment yield to be identified and has revealed that the nature of the resulting relationships can be quite varied. Explanations for diversity in the relationships between sediment yield and catchment variables within the Upper Yangtze are summarized below.

Grouping by tributary provided a number of significant relationships for two tributary groups. Multiple regression using six catchment variables indicates that 87 and 95 per cent of the variance in sediment yields can be explained in the Jinsha–Yalong and Dadu–Min, respectively. In contrast, only 33 per cent of the variance is explained in the Jialing. This contrast reflects the larger human impact in the Jialing. The six selected catchment variables reflect topographic and climatic variables which can be extracted from global data sets. Population density is the only variable that relates to human impact. Clearly, the inclusion of land use, soils and geological information would greatly strengthen attempts to model regional sediment yields. Unfortunately, the resolution of digital information on these variables available within the public domain is not yet sufficient to support extraction of necessary catchment variables. As land use, geology and soil impacts are relatively local, analysis of larger catchments generates clearer results than analysis of smaller ones. The strong, inverse relationship between sediment yield and mean elevation in the >100 000 km^2 category reflects the fact that elevation is acting as a surrogate for low precipitation, runoff and human impact. The nature of the relationship between elevation and sediment yield contradicts all previous studies of regional or global sediment yields (e.g. Milliman and Syvitski, 1992) but can be attributed to the particular geography of the Upper Yangtze. The high elevation portions of the catchment are areas of gentle relative relief, limited precipitation and low human activity. Consequently, fluvial erosion in most of Tibet is limited and does not export much sediment beyond the plateau (Fielding *et al.*, 1994). Comparatively severe soil erosion on agricultural land, particularly around the margin of the Sichuan Basin, means that sediment yields are relatively high at elevations below 5000 m.

Population density can be used as an indicator of the extent and intensity of human impact within the Upper Yangtze Basin. Its relationship to sediment yield is positive in catchments with higher maximum elevations and larger areas, but is otherwise scattered. In the Jialing tributary there is a negative relationship between sediment yield and population density. The variability of this relationship deserves further consideration in four main respects. First, it should be noted that the population density data are derived from the 1992 census, while the sediment yield data are averages from the period 1956–1987. During the last 40 years there have been significant changes in the number and distribution of people living in the Upper Yangtze Basin, so that

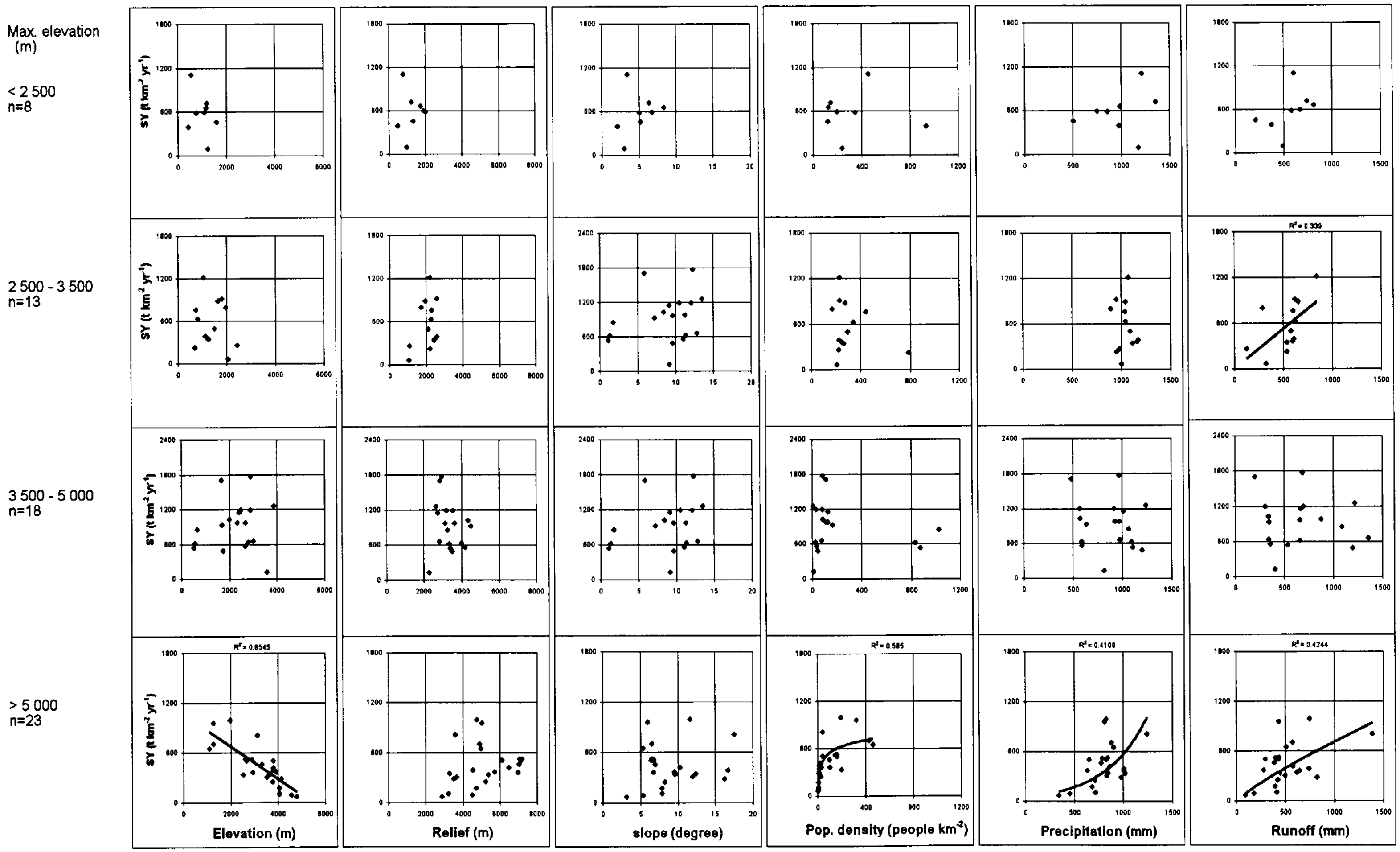

Figure 7. Relationships between specific sediment yield and catchment variables for the data grouped by maximum elevation

the statistical relationships must be treated with caution owing to non-stationarity in the population data. Second, population density is in any case only a crude measure of human impact. The largest concentrations of population are in the relatively flat areas of the Sichuan Basin, whereas the most severe soil erosion occurs on the sloping land around the margins of this area. Third, much of the reported increase in soil erosion in central China during the measurement period is associated with deforestation and/or expansion of agricultural activities. By its nature, this tends to be in areas *adjacent* to high population densities. Further work is required to model the temporal impact of land disturbance on sediment yield. Fourth, the measurement period has coincided with a phase of widespread construction of water conservancy structures. Much of the sediment derived from soil erosion in the higher population areas of the Upper Yangtze may be being trapped in temporary storage in ditches, ponds and reservoirs. Indeed, storage in small reservoirs may account for the discrepancy between estimates of increasing soil erosion in the Upper Yangtze and the lack of an upward trend in sediment yield measured at Yichang (Higgitt and Lu, 1996).

Generally, sediment yield increases with precipitation and runoff in most groupings but displays polynomial relationships in the Jialing tributary and in catchments in the 10 000–100 000 km^2 size category. This variation reaffirms the contention that no simple relationship exists between these variables (Walling and Webb, 1983). A general increase with precipitation is consistent with other regional and global analyses (Probst and Amiotte-Suchet, 1992; Ludwig and Probst, 1996). Xu (1994), using data from 700 rivers in China, suggested sediment yield attains a maximum for around 400 mm of runoff. This implies that sediment yields in China fit the Langbein and Schumm (1958) model and are therefore primarily a natural phenomenon. There is little support for this conclusion in the data for the Upper Yangtze. Multiple regression results suggest that much of the sediment yield variability in the west of the basin can be attributed to natural phenomena, but that topographic and climatic variables afford relatively little explanation of sediment yields in the agricultural, eastern portion of the basin.

The increasing availability and improving resolution of global, environmental databases offers the prospect of examining the relationships between fluvial sediment yield and various catchment properties within a GIS framework. To date, GIS-based studies have tended to focus on either global-scale variations or comparisons between different catchments in a regional context. The analysis of variation *within* large catchments offers considerable potential for the investigation and management of sediment-related problems. In the case of the Upper Yangtze Basin, the attention of environmentalists worldwide has been drawn to the region by the Three Gorges Project. Integration of sediment yield records and environmental databases within a GIS not only provides a basis for the empirical investigation of controls on the patterns of sediment yield but also provides a platform for predictive modelling. However, procedures for dealing with hierarchical data from a series of nested catchments must be enhanced to deal with a number of problematic issues. Perhaps the most pressing issues concern development of improved approaches to standardizing specific sediment yields to account for catchment size and scale effects. Also, mapping conventions for representing sediment yield within a series of nested catchments are problematic and include shading polygons of incremental catchment area, point interpolation procedures, predictions from regression models or residuals from whole catchment yield–area relationships (Higgitt and Lu, 1996; Lu and Higgitt, 1998b)

CONCLUSION

The utility of GIS to extract spatially distributed data for the analysis of intra-catchment sediment yields has been demonstrated. At the time of writing detailed information on land use, geology and soils is not in the public domain and the examination of sediment yield variability in the Upper Yangtze Basin has been confined to six variables: mean elevation, basin relief, mean slope, mean annual runoff, mean annual precipitation and population density. Several of these variables are strongly correlated with one another, necessitating caution when interpreting the results of multiple regression analyses. A high degree of scatter in the sediment yield data results from the diverse characteristics of the catchment, and this has been reduced by grouping the data into categories based on geographic location, catchment size and maximum elevation, prior to analysis.

The results generally indicate that specific sediment yields increase with precipitation, runoff, population density and mean slope, but decrease with elevation. Elevation is strongly correlated with other catchment

variables and is therefore an influential factor on sediment yields, although it has little direct effect on erosion dynamics. The geography of the Upper Yangtze catchment means that high elevation areas are mostly flat, semi-arid and sparsely populated, with limited agricultural activity. Within the bivariate plots of sediment yield against catchment variables some interesting contrasts emerge, particularly with regard to precipitation and runoff. Of particular significance is apparent scale dependency in the nature of the relationship for sediment yield as a function of elevation, precipitation and runoff. Further attention to removing scale effects from the analysis of controls on sediment yields is required.

The limited number of variables used in this study are capable of explaining the majority of the variance of the measured specific sediment yield for the Jinsha–Yalong and Dadu–Min tributaries, but perform less well in the more heavily populated areas. The results indicate that topographic, climatic and crude human impact variables provide a reasonable explanation of sediment yield variations in comparatively natural environments, but are inadequate in regions influenced by large-scale agricultural activity. It is envisaged that the resolution of global data sets will continue to improve, allowing the incorporation of variables representing geological, soil and human activity conditions into regional studies of sediment yield.

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REFERENCES

Douglas, I. 1967. 'Man, vegetation and the sediment yield of rivers', *Nature*, **215**, 925–928.

Edmonds, R. L. 1992. 'The Sanxia (Three Gorges) Project: the environmental argument surrounding China's super dam', *Global Ecology and Biogeography Letters*, **2**, 105–125.

ESRI 1994. Cell-based modelling with GRID, ArcDoc version 7·0·2 on-line help.

Fielding, E., Isacks, B., Barazangi, C. and Duncan, C. 1994. 'How flat is Tibet?', *Geology*, **22**, 163–167.

Gu, H. Y. and Douglas, I. 1989. 'Spatial and temporal dynamics of land degradation and fluvial erosion in the middle and upper Yangtze River basin, China', *Land Degradation and Rehabilitation*, **1**, 217–235.

Gu, H. Y., Ai, N. S. and Ma, H. L. 1987. 'Sediment sources and trend of sedimentation in the Three Gorges reservoir area', in Leading Group of the Three Gorges Project Ecology and Environment Research Project, Chinese Academy of Sciences (Ed.), Collected Papers on Ecological and Environmental Impact of The Three Gorges Project and Countermeasures, Science Press, Beijing, 522–541 (in Chinese).

Higgitt, D. L. and Lu, X. X. 1996. 'Patterns of sediment yield in the Upper Yangtze Basin, China', in Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996), IAHS Publication 236, 205–214.

Jansen, J. M. L. and Painter, R. B. 1974. 'Predicting sediment yield from climate and topography', *Journal of Hydrology*, **21**, 371–380.

Jansson, M. B. 1988. 'A global survey of sediment yield', *Geografiska Annaler*, **70A**, 81–98.

Lajczak, A. and Jansson, M. B. 1993. 'Suspended sediment yield in the Baltic drainage basin', *Nordic Hydrology*, **24**, 31–52.

Langbein, W. B. and Schumm, S. A. 1958. 'Yield of sediment in relation to mean annual precipitation', *Transactions of the American Geophysical Union*, **39**, 1076–1084.

Legates, D. R. and Willmost, C. J. 1992. 'Monthly average surface air temperature and precipitation. Digital Raster Data on a 30 minutes Geographic (lat/long) 360*720 grid', in Global Ecosystems Database Version 1·0, Disc A, NOAA National Geophysical Data Centre Boulder, CO.

Lu, X. X. and Higgitt, D. L. 1998a. 'Recent changes of sediment yeild in the Upper Yangtze, China', *Environmental Management*, **22**, 697–709.

Lu, X. X. and Higgitt, D. L. 1998b. 'Sediment yield mapping using GIS in the Upper Yangtze', in Cao, Z. H. (Ed.), International Symposium on Soil, Human and Environment Interactions (Nanjing, China, 1997), China Science Technology Press, Beijing, 40–50.

Ludwig, W. and Probst, J. L. 1996. 'A global modelling of the climatic, morphological, and lithological control of river sediment discharges to the oceans', in Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996), IAHS Publication 236, 21–28,

Milliman, J. D. and Syvitski, J. P. M. 1992. 'Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers', *Journal of Geology*, **100**, 525–544.

NOAA-EPA Global Ecosystem Project 1992. Global Ecosystems Database Version 1·0, User's Guide, Documention, Reprints, and Digital Data on CD-ROM, USDOC/NOAA National Geophysical Data Center, Boulder, CO.

Ozturk, F. 1996. 'Suspended sediment yields of rivers in Turkey', in Erosion and Sediment Yield: Global and Regional Perspectives (Proceedings of the Exeter Symposium, July 1996), IAHS Publication 236, 65–71.

Probst, J. L. and Amiotte-Suchet, P. 1992. 'Fluvial suspended sediment transport and mechanical erosion in the Maghreb (North Africa)', *Hydrological Sciences Journal*, **37**, 621–637.
Qian, N., Zhang, R. and Chen, Z. C. 1993. 'Some aspects of sedimentation at the Three Gorges Project', in Luk, S-H. and Whitney, J. B. (Eds), Megaproject A, Case Study of China's Three Gorges Project, M.E. Sharpe, Armonk, NY, 121–160.
Ruddiman, W. F., Prell, W. L. and Raymo, M. E. 1989. 'Late Cenozoic uplift in southern Asia and the American West: Rationale for general circulation modeling experiments', *Journal of Geophysical Research*, **94**, 18, 379–18, 391.
Summerfield, M. A. and Hulton, N. J. 1994. 'Natural controls of fluvial denudation rates in major world drainage basins', *Journal of Geophysical Research*, **99**(B7), 13, 871–13, 883.
Walling, D. E. 1983. 'The sediment delivery problem', *Journal of Hydrology*, **65**, 209–237.
Walling D. E. 1983 'Patterns of sediment yield', in Gregory, K. J. (ED), Background to palaeohydrology, Wiley, Chichester 65–100.
Waythomas, C. F. and Williams, G. P. 1988. 'Sediment yield and spurious correlation – Toward a better portrayal of the annual suspended sediment load of rivers', *Geomorphology*, **1**, 309–316.
Wen, D. Z. 1993. 'Soil erosion and conservation in China', in Pimental, D. (Ed.), World Soil Erosion and Conservation, Cambridge University Press, Cambridge, 63–85.
Wilson, L. 1973. 'Variation in mean annual sediment yield as a function of mean annual precipitation', *American Journal of Science*, **273**, 335–349.
Xu, J. X. 1994 'Zonal distribution of river basin erosion and sediment yield in China', *China Science Bulletin*, **39**, 1356–1361.
Zhou, G. Y. and Xiang, Z. 1994. 'Sediment transport in the Yangtze basin', in Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994), IAHS Publication 224.

